Opportunities for New Physics at Super(Hyper)-Kamiokande

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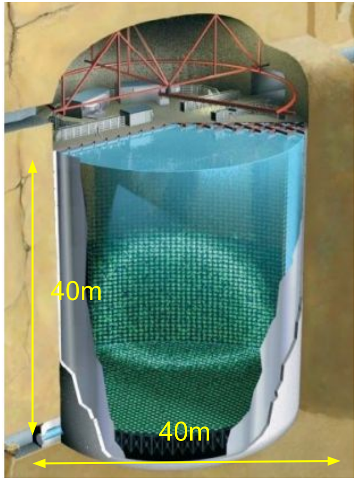
Super-Kamiokande (SK)

- 50 kton water Cherenkov multipurpose experiment in Japan
- Running since 1996 (SK phases I-VII)
- Around 11,000 PMTs inner detector, with outer detector
- Gadolinium-doped (SK-Gd)[1] water since 2020 for easier capture neutron identification

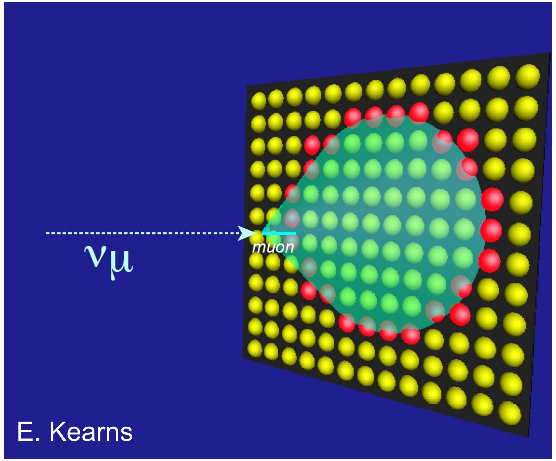


Phase	SK-I	SK-II	SK-III	SK-IV
Begin	Apr. 1996	Dec. 2002	July 2006	Sep. 2008
End	June 2001	Nov. 2005	Sep. 2008	June 2018
ID PMTs	11,146	5,182	11,129	11,129
Electronics	ATM	ATM	ATM	QBEE
Trigger	Hardware	Hardware	Hardware	Software
DSNB trigger	SHE	SHE	SHE	SHE+AFT
Water	pure	pure	pure	pure
Phase	**SK-V**	**SK-VI**	**SK-VII**	**Total**
Begin	Feb. 2019	July 2020	June 2022	Apr. 1996
End	July 2020	June 2022	(running)	(running)
ID PMTs	11,129	11,129	11,129	-
Electronics	QBEE	QBEE	QBEE	-
Trigger	Software	Software	Software	-
DSNB trigger	SHE+AFT	SHE+AFT	SHE+AFT	-
Water	pure	0.01% Gd	0.03% Gd	-

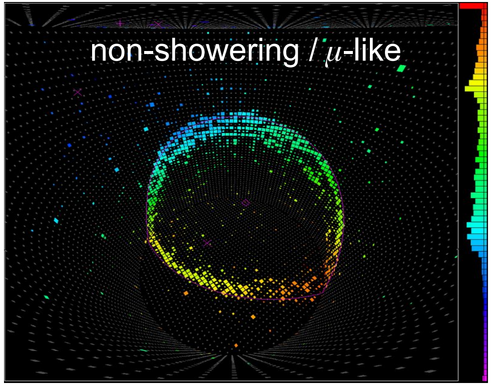
~ hundreds international scientists

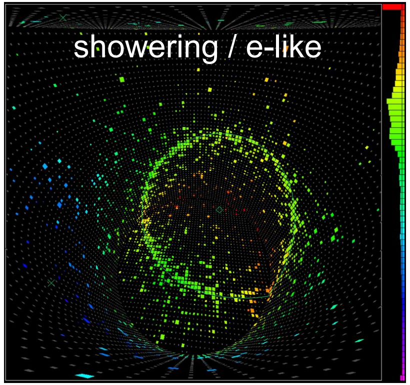
[1] proposal [Beacom, Vagins, *PRL*, 2003]

Water Cherenkov Detection Principle



real SK data (1998)





- Cherenkov radiation
  - charged particle travels in medium faster than light → builds wave-front emission

Super-K Truly Spectacular Multipurpose Experiment

- **Discovery of neutrino oscillations**

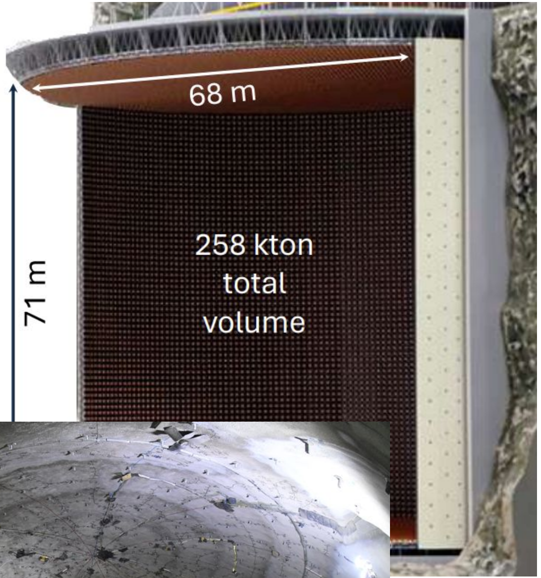
- **Best** supernova-ν, nucleon-decay detector in the world

- **Excellent** for multipurpose physics studies (~10 - 10^4 MeV)
  - ν-oscillations, Lorentz invariance tests, sterile-ν
  - baryon-violating processes (proton decay, di-nucleon decay, n-nbar, etc.)
  - solar-ν, solar (g)ravity modes, day/night effect, SN-ν, DSNB (SN relic ν's)
  - (in)direct DM searches
  - exotics (monopoles, Q-balls, millicharge particles, etc.)
  - ….

- SK aims for first detection of Diffuse SN Neutrino Background (DSNB) within few years

Into the Future with Hyper-Kamiokande (HK)

- Next generation neutrino observatory in Japan, 260 kton water Cherenkov experiment
- Construction began, data taking planned for 2027
- **Big progress:** access tunnel completed, dome completed, cavern excavation underway

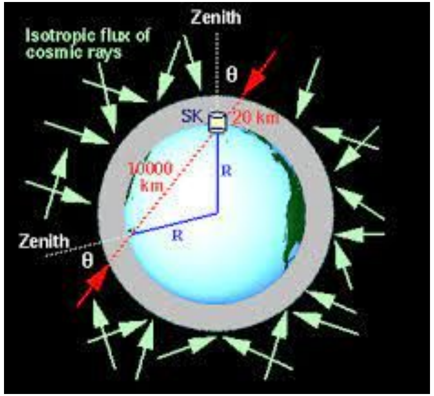


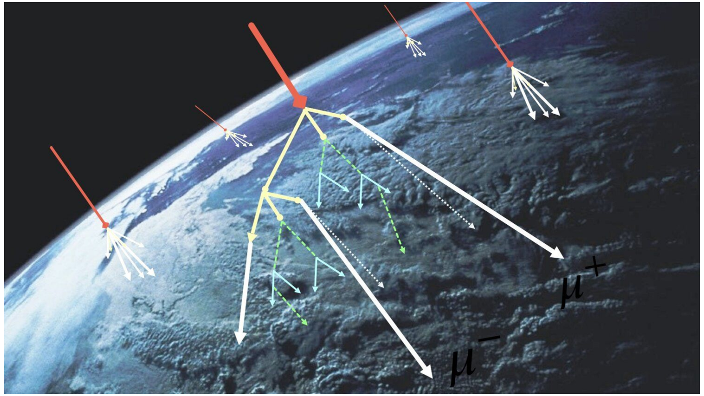
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% ($\times$2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton

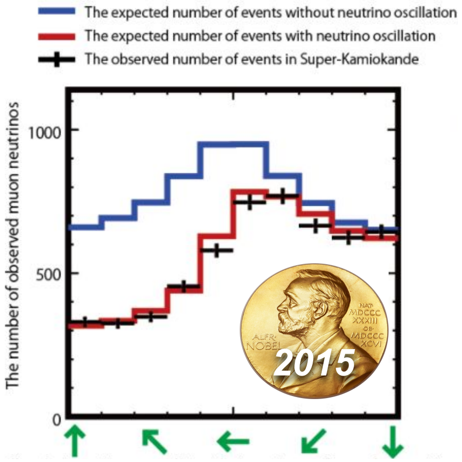
SK / HK - New Physics Discovery Machines

SK Discovery of Neutrino Oscillations

- Cosmic rays isotropically bombarding atmosphere lead to copious production of neutrinos
  → **fundamental discovery of neutrino oscillations** [Fukuda+ (Super-K), *PRL*, 1998]



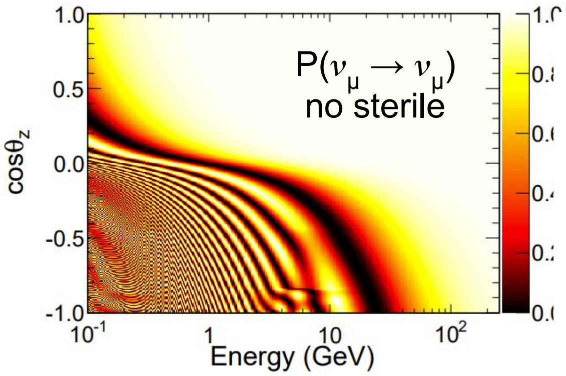


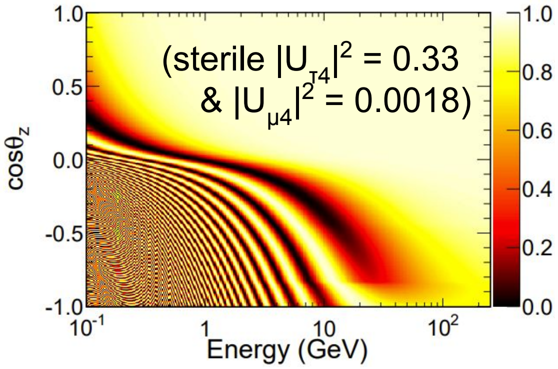


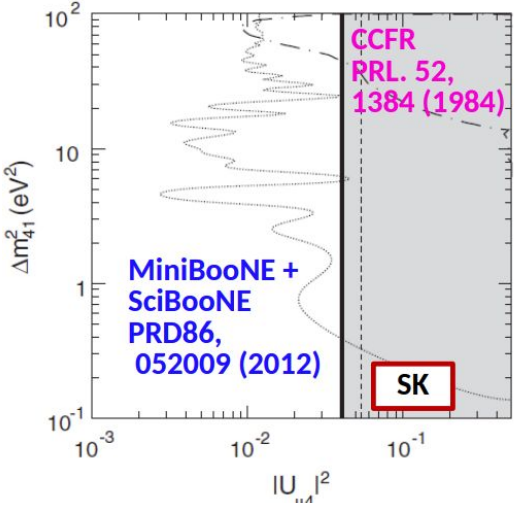
Atmospheric Oscillations: Sterile Neutrinos

- With standard oscillation parameters quite well known, atmospheric neutrinos allow for sensitively searching of other exotic / new physics processes

$$\tilde{H} = U_{\mathrm{PMNS}} M^{(3)} U^{\dagger}_{\mathrm{PMNS}} + V_e \pm \frac{G_F N_n}{\sqrt{2}} \sum_{\alpha=\mathrm{sterile}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & |\tilde{U}_{\alpha 2}|^2 & \tilde{U}^*_{\alpha 2}\tilde{U}_{\alpha 3} \\ 0 & \tilde{U}_{\alpha 2}\tilde{U}^*_{\alpha 3} & |\tilde{U}_{\alpha 2}|^2 \end{pmatrix}$$





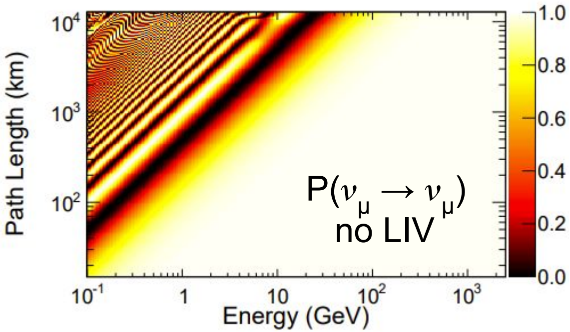


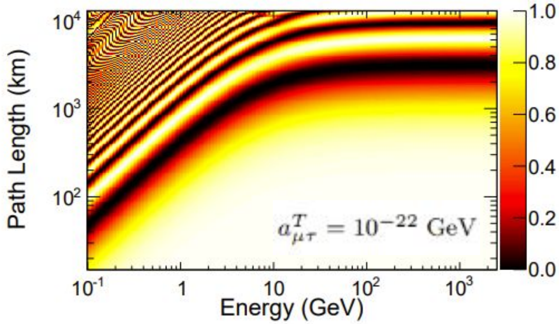
[Abe+ (Super-K), *Phys.Rev.D*, (2015)]

Atmospheric Oscillations: Lorentz Invariance Tests

$$\tilde{H} = U_{\mathrm{PMNS}} M^{(3)} U^{\dagger}_{\mathrm{PMNS}} + V_e \ + H_{LV}(a, c)$$

Coefficient	Unit	d	CPT	Oscillation Effect
Isotropic				
$a^{T}_{\alpha\beta}$	GeV	3	odd	$\propto L$
$c^{TT}_{\alpha\beta}$	-	4	even	$\propto LE$
Directional				
$a^{X}_{\alpha\beta}, a^{Y}_{\alpha\beta}, a^{Z}_{\alpha\beta}$	GeV	3	odd	sidereal variation
$c^{XX}_{\alpha\beta}, c^{YZ}_{\alpha\beta}, \ldots$	-	4	even	sidereal variation





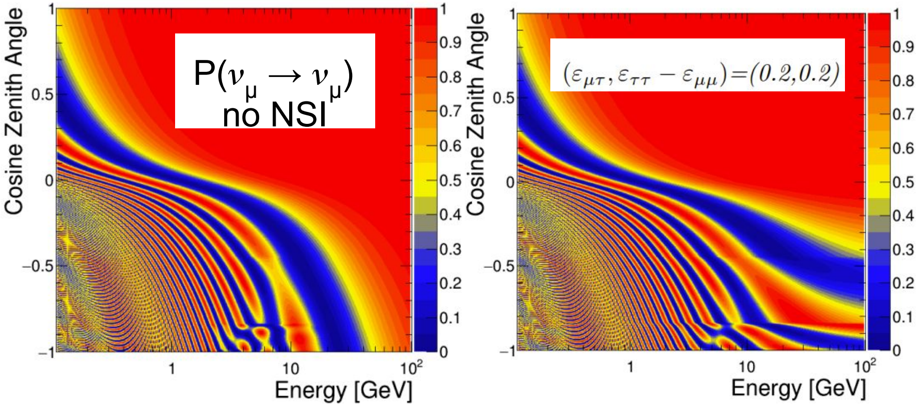
	LV Parameter	Limit at 95% C.L.
$e\mu$	Re (a^T)	1.8×10^{-23} GeV
	Im (a^T)	1.8×10^{-23} GeV
	Re (c^{TT})	8.0×10^{-27}
	Im (c^{TT})	8.0×10^{-27}
$e\tau$	Re (a^T)	4.1×10^{-23} GeV
	Im (a^T)	2.8×10^{-23} GeV
	Re (c^{TT})	9.3×10^{-25}
	Im (c^{TT})	1.0×10^{-24}
$\mu\tau$	Re (a^T)	6.5×10^{-24} GeV
	Im (a^T)	5.1×10^{-24} GeV
	Re (c^{TT})	4.4×10^{-27}
	Im (c^{TT})	4.2×10^{-27}

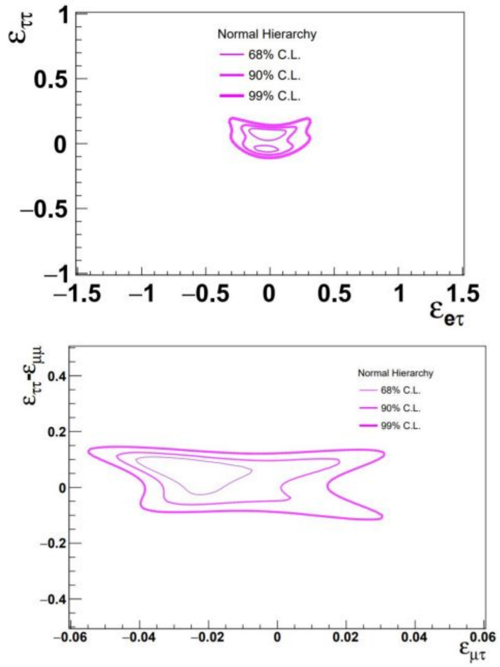
- SK most sensitively probes Lorentz Invariance Violation (LIV) for some EFT coefficients

[Abe+ (Super-K), *Phys.Rev.D*, (2015)]

Atmospheric Oscillations: Non-Standard Interactions (NSI)

$$\tilde{H} = U_{\rm PMNS} M^{(3)} U^{\dagger}_{\rm PMNS} \pm \sqrt{2} G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

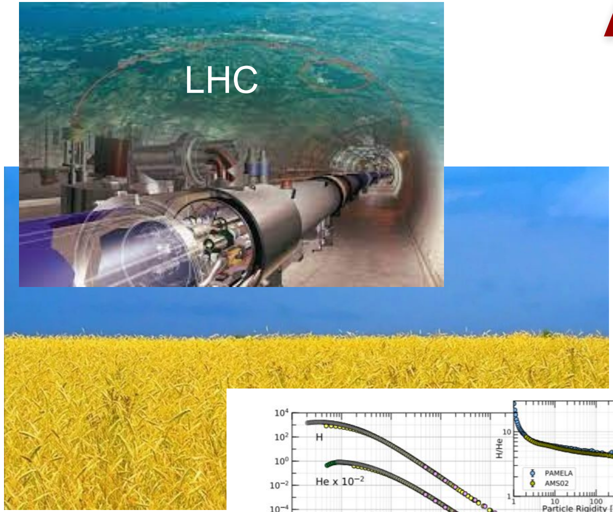


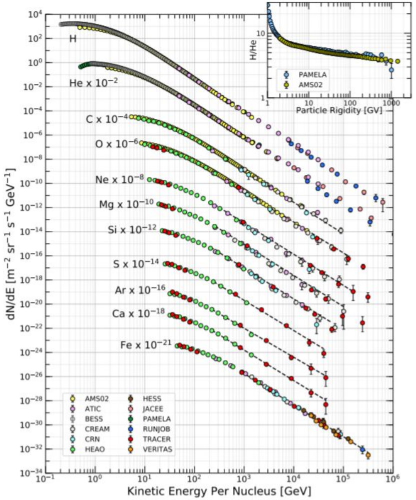


[Mahdi (Super-K), PhD Thesis, (2015)]

- SK can also sensitively test solar neutrino NSI [Weatherly+ (Super-K), arXiv:*2203.11772*, (2022)]

Atmospheric Collider

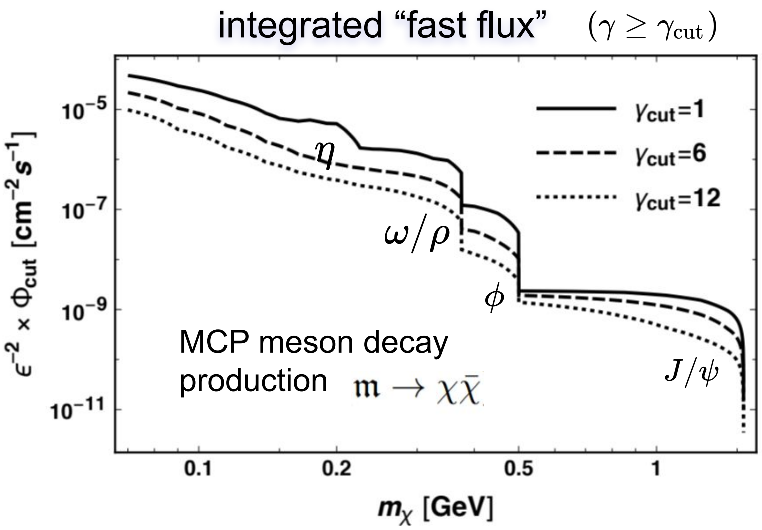


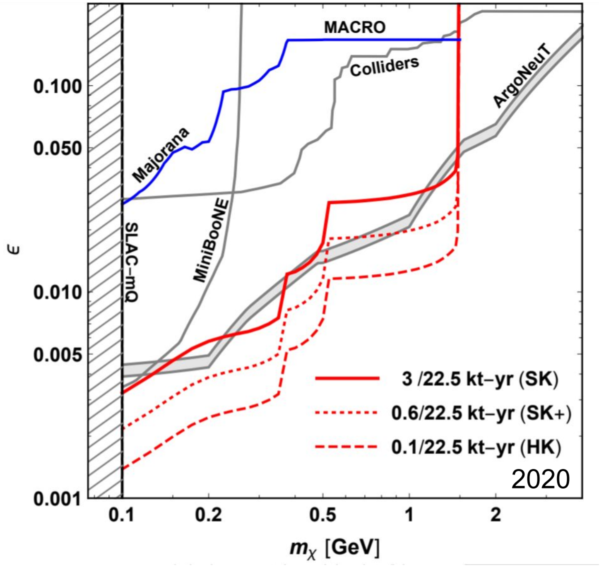


- ***Unique natural source*** of ~p collisions
- “Beam” is ***always ON***
- Robust flux for ***ALL*** terrestrial experiments
- Broad energy spectrum

⇨ **excellent opportunities for exploration of fundamental physics**

Atmospheric Collider: Millicharge & SIDM (Direct Detection)





can reinterpret as limits on strongly-interacting DM (SIDM)

- First quantitative exploration of idea → SK/HK probes broad parameter space

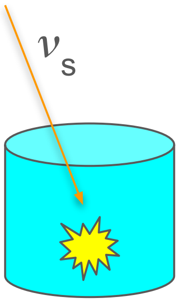
  * detailed subsequent numerical simulations [Argüelles, Kelly, Munoz, *JHEP*, (2021)]

  * further refinements [Du+, 2022]

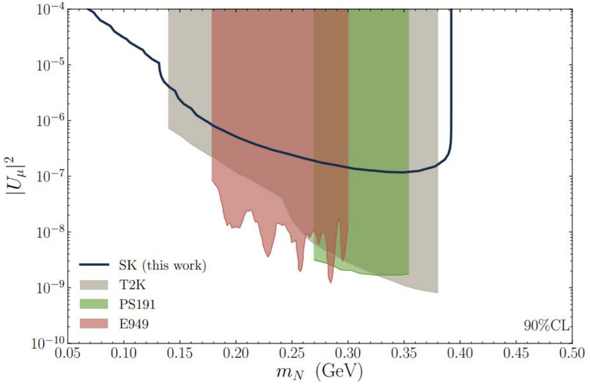
[Plestid, **VT**, Tsai, Bringmann, Kusenko, Pospelov, *Phys.Rev.D*, (2020)]

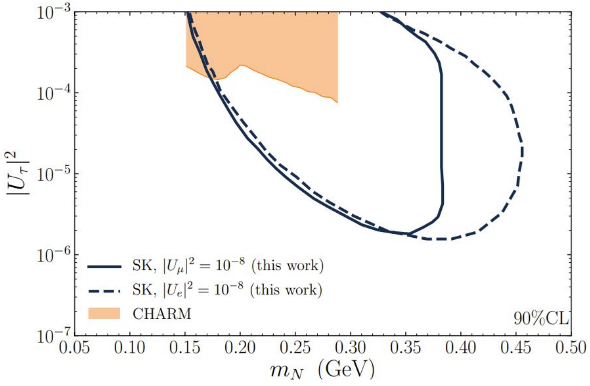
Atmospheric Collider: Heavy Neutral Leptons (HNL)

meson decays



visible decays





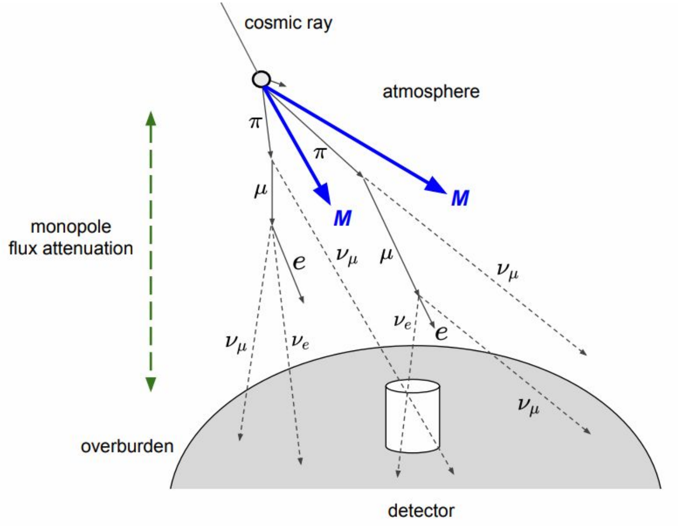
[Coloma, Hernández, Munoz, Shoemaker, *EPJC,* (2020)]

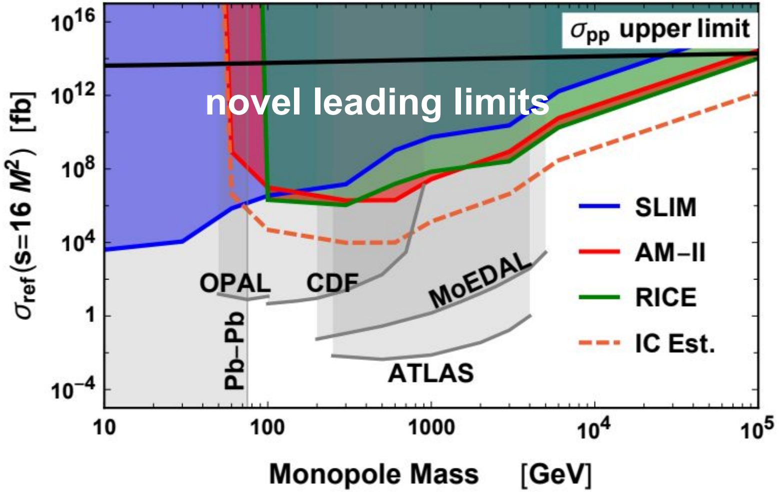
… connection to Hubble tension? [Gelmini, Kusenko, **VT**, *JCAP,* (2019)]

- Another twist: "Double Bang" events as ν's upscatter to HNLs decaying to visible states

[Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker, *JHEP,* (2022)]

Aside: Monopoles from Atmospheric Collider



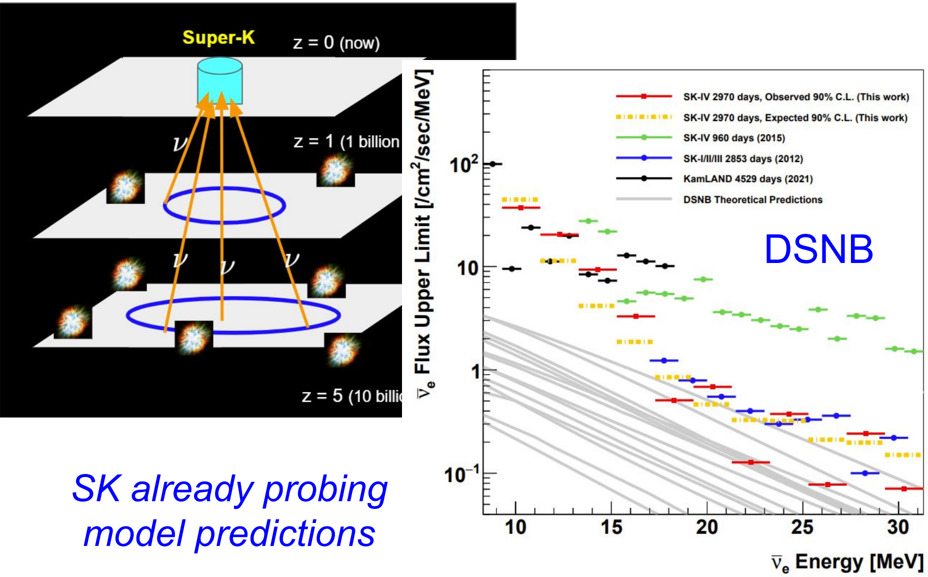


- Atm. collider gives robust universal flux source, sets leading bounds, connects historic studies

resolve decades-old problem of interpreting ambient monopole searches

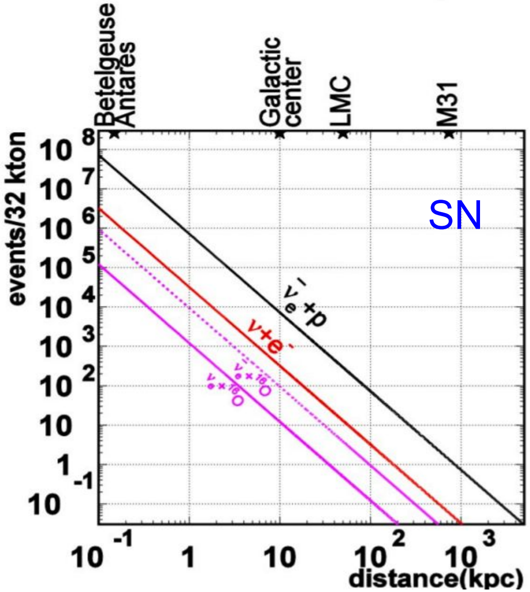
[Iguro, Plestid, **VT**, *Phys.Rev.Lett.*, (2021)]

Supernova, DSNB and New Neutrino Physics



SK already probing model predictions

[Abe+ (Super-K), *Phys.Rev.D*, (2021)]



5MeV threshold

~7,300 $\bar{\nu}_e$+p events
~300 ν+e events
~100 $\overset{(-)}{\nu}_e$+^{16}O events

for 10 kpc supernova

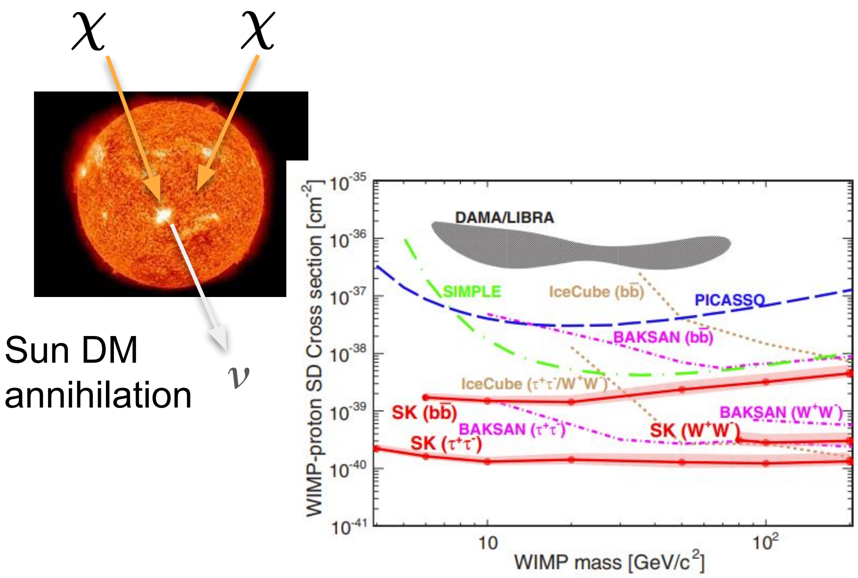
[M. Nakahata]

- New neutrino physics can impact SN as well as DSNB signatures

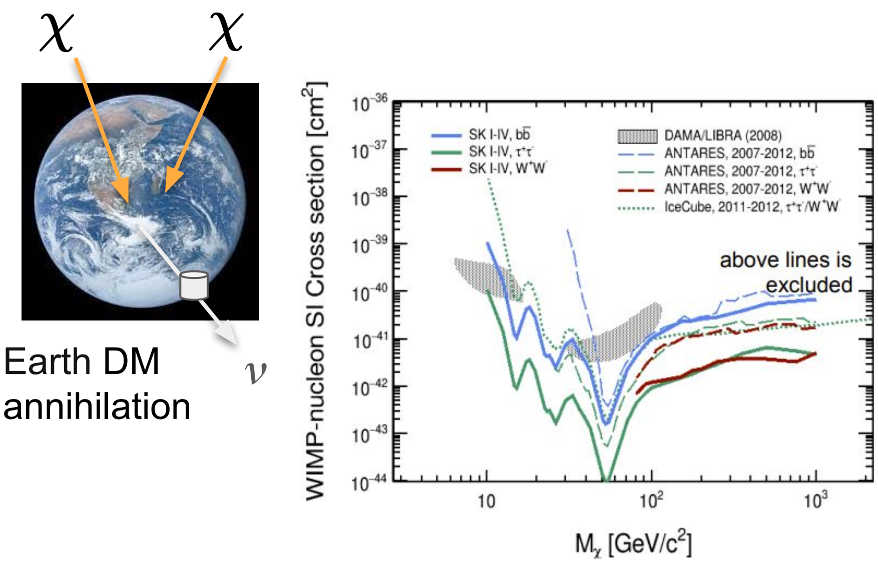
(e.g. NSI [Lei, Steinberg, Wells, *JHEP*, (2019)], pseudo-Dirac nature [de Gouvea+, *PRD*, (2020)], decays and beyond MSW [Tabrizi, Horiuchi, *JCAP*, (2021)], sterile interactions [Balantekin+, *PRD*, (2023)])

Indirect Dark Matter Searches

WIMP DM annihilation: $\chi\chi \rightarrow \nu\bar{\nu}, W^{+}W^{-}, b\bar{b}, \mu^{+}\mu^{-} \rightarrow \ldots \nu_{e/\mu/\tau}$

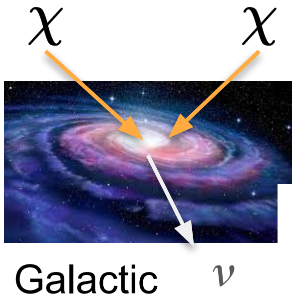


[Choi+ (Super-K), *Phys.Rev.Lett*, (2015)]

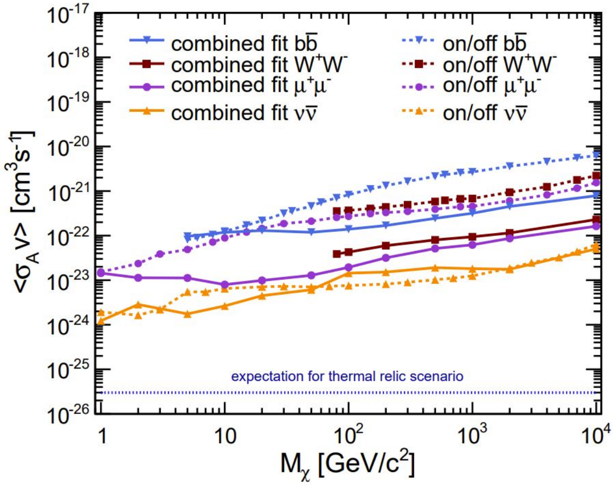


[Frankiewicz (Super-K), PhD Thesis, (2018)]

Indirect Dark Matter Searches

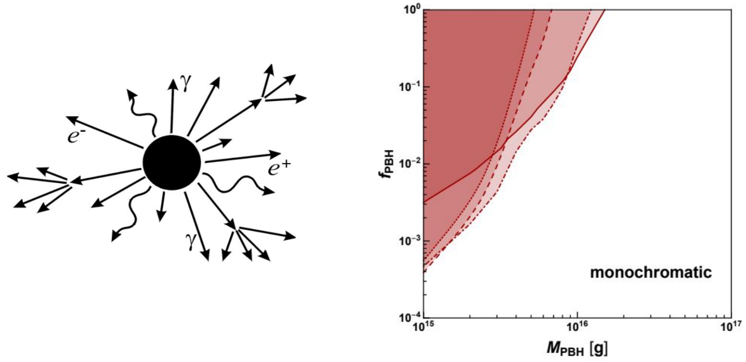


Galactic Center DM annihilation



[Abe+ (Super-K), *Phys.Rev.D*, (2020)]

SK has sensitivity beyond WIMPs, e.g. ν's from primordial black hole DM Hawking evaporation



[Dasgupta+, *Phys.Rev.Lett.*, (2020)]

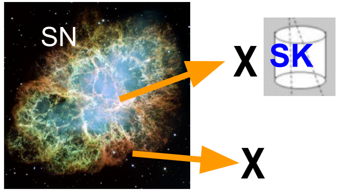
also evaporation to SK-interacting axions

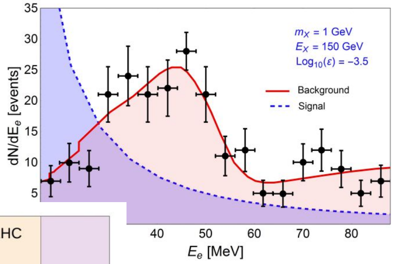
[Li, Zhang, *Phys.Rev.*D, (2022)]

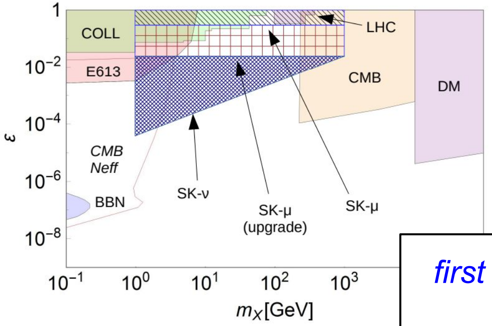
Direct Dark Matter Searches

- SK (HK) can directly probe ("boosted", BDM) DM interactions, mechanisms beyond Atm. Coll.
  → several ongoing SK analyses, especially with Low-E <100 MeV data

Cosmic Accelerator





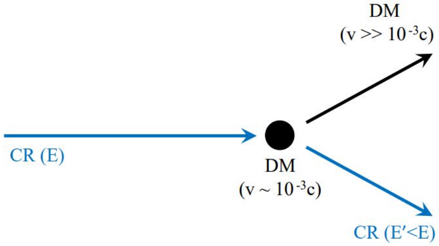


astro flux

$\sim E^{-\alpha}$

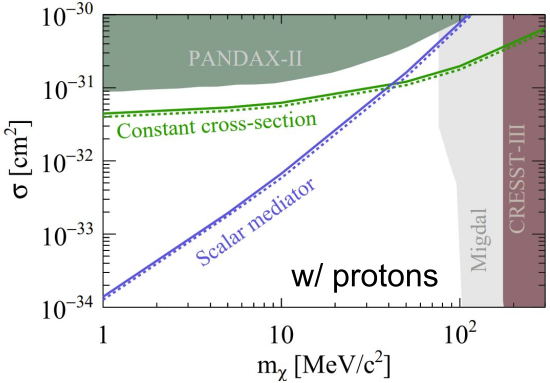
first Low-E "BDM" proposal

[Hu, Kusenko, **VT**, *Phys.Lett.B*, (2016)]
(follow ups [Dunsky+, JCAP, (2019); Li, Lin, *PRD*, 2019])



[Cappiello, Beacom, 2019;
Bringmann, Pospelov, 2019;
Ema+, 2019]

Cosmic-ray Upscattering



w/ protons [Abe+ (Super-K), *Phys.Rev.Lett.*, (2023)]

Boosted DM from Galactic Center (Sun) Annihilation/Decays

w/ electrons [Kachulis+ (Super-K), *Phys.Rev.Lett.*, (2016)]

[Agashe, Cui, Necib, Thaler, *JCAP*, (2014);
inelastic [Giudice, Kim, Park, Shin, *Phys.Lett. B*, (2018)] + many

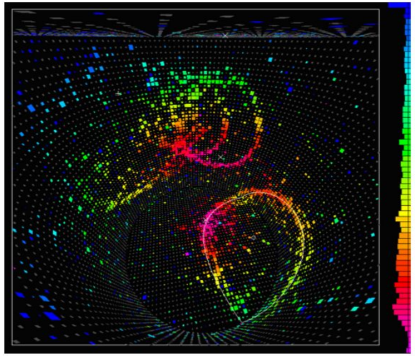
Nucleon Decays

- In Standard Model baryon number conserved*
  → proton stable

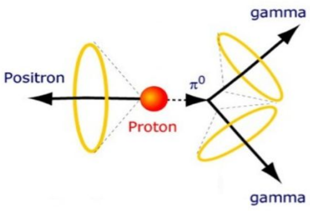
- Nucleon decays generic predictions of motivated theories (e.g. GUTs, supersymmetry)

- 30+ channels studied at Super-K, with best limits

Decay Mode	$\lvert\Delta(B-L)\rvert$	τ/B (90%C.L.)	Reference
$p \to e^+\pi^0$	0	1.7×10^{34} yrs.	[22]
$p \to \mu^+\pi^0$	0	7.8×10^{33} yrs.	[22]
$p \to \nu K^+$	$0(\overline{\nu}), 2(\nu)$	6.6×10^{33} yrs.	[25]
$p \to \mu^+ K^0$	$0(\overline{\nu}), 2(\nu)$	6.6×10^{33} yrs.	[23]
$p \to e^+\eta$	0	4.2×10^{33} yrs.	[13]
$p \to \mu^+\eta$	0	1.3×10^{33} yrs.	[13]
$p \to e^+\rho^0$	0	7.1×10^{32} yrs.	[13]
$p \to \mu^+\rho^0$	0	1.6×10^{32} yrs.	[13]
$p \to e^+\omega^0$	0	3.2×10^{32} yrs.	[13]
$p \to \mu^+\omega^0$	0	7.8×10^{32} yrs.	[13]
$p \to \nu\pi^+$	$0(\overline{\nu}), 2(\nu)$	3.9×10^{32} yrs.	[38]
$p \to e^+\nu\nu$	$0(\overline{\nu}\nu), 2(\nu\nu, \overline{\nu}\overline{\nu})$	1.7×10^{32} yrs.	[36]
$p \to \mu^+\nu\nu$	$0(\overline{\nu}\nu), 2(\nu\nu, \overline{\nu}\overline{\nu})$	2.2×10^{32} yrs.	[36]
$p \to e^+ X^a$	$0(X?)$	7.9×10^{32} yrs.	[37]
$p \to \mu^+ X^a$	$0(X?)$	4.1×10^{32} yrs.	[37]
$n \to e^+\pi^-$	0	2.0×10^{33} yrs.	[13]
$n \to \mu^+\pi^-$	0	1.0×10^{33} yrs.	[13]
$n \to e^+\rho^-$	0	7.0×10^{31} yrs.	[13]
$n \to \mu^+\rho^-$	0	3.6×10^{31} yrs.	[13]
$n \to \nu\pi^0$	$0(\overline{\nu}), 2(\nu)$	1.1×10^{33} yrs.	[38]
$n \to \nu\gamma$	$0(\overline{\nu}), 2(\nu)$	5.5×10^{32} yrs.	[37]
$pp \to K^+K^+$	2	1.7×10^{32} yrs.^{b}	[32]
$pp \to \pi^+\pi^+$	2	7.2×10^{31} yrs.^{b}	[33]
$np \to e^+\nu$	$0(\overline{\nu}), 2(\nu)$	2.6×10^{32} yrs.^{b}	[37]
$np \to \mu^+\nu$	$0(\overline{\nu}), 2(\nu)$	2.0×10^{32} yrs.^{b}	[37]
$np \to \tau^+\nu$	$0(\overline{\nu}), 2(\nu)$	3.0×10^{31} yrs.^{b}	[37]
$np \to \pi^+\pi^0$	2	1.7×10^{32} yrs.^{b}	[33]
$nn \to \pi^0\pi^0$	2	4.0×10^{32} yrs.^{b}	[33]
$n - \overline{n}$ oscillations	2	1.9×10^{32} yrs.	[27]



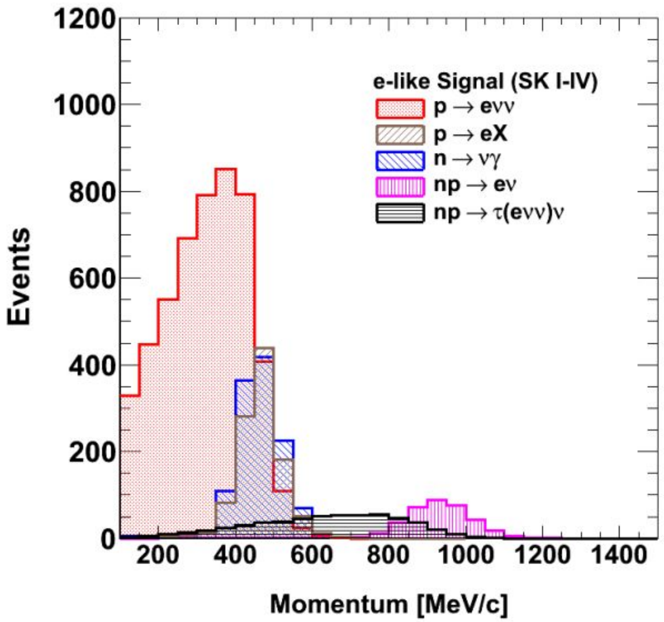
$$p \to e^+\pi^0$$

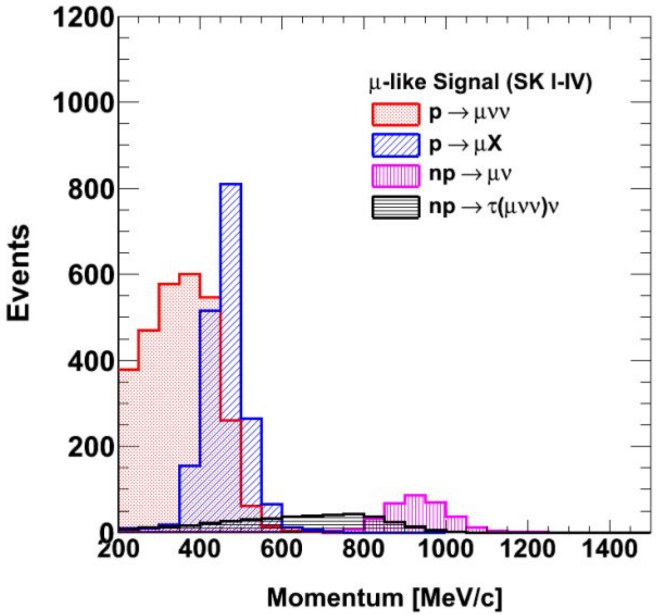


often dominant channel in GUTs

e.g. [**VT** (Super-K), Moriond 2016 Proc., arXiv:1605.03235]

Nucleon Decay Spectral Searches





[**VT+** (Super-K), *Phys.Rev.Lett.*, (2014)]
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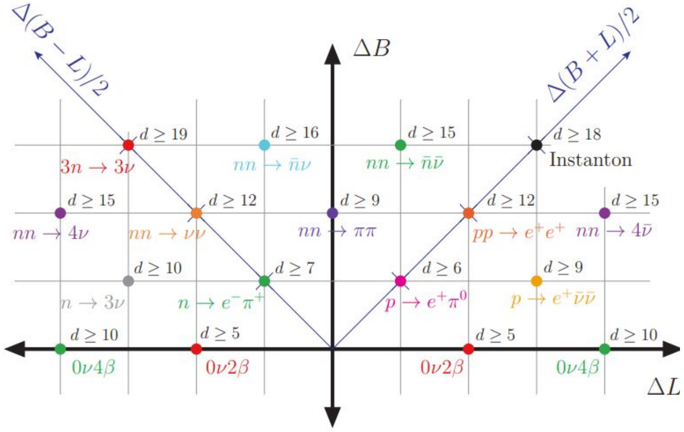
+ ongoing SK analyses

- Look for visible energy-momentum, distribution is essential [Chen, **VT**, *Phys.Rev.D*, (2014)]

Many Channels Still Unexplored



Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [65]
$n \to \nu + e^- + \mu^+$	0,2	83 [65]
$n \to \nu + e^+ + \mu^-$	0,2	83* [65]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [65]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [62] (52* [65])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [65]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [62] (74* [65])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [65]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [65]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$pn \to e^+ + \nu$	0,2	260 [28]
$pn \to \mu^+ + \nu$	0,2	200 [28]
$pn \to \tau^+ + \nu$	0,2	29 [28]
$pn \to \gamma + \pi^+$	2	
$pn \to \gamma + \rho^+$	2	
$pn \to \gamma + K^+$	2	
$pn \to \gamma + K^{*,+}$	2	
$pn \to \gamma + D^+$	2	
$pn \to \pi^+ + \pi^0$	2	170 [115]
$pn \to \eta + \pi^+$	2	
$pn \to \pi^+ + \rho^0$	2	
$pn \to \pi^+ + \omega$	2	
$pn \to \eta' + \pi^+$	2	
$pn \to K^0 + \pi^+$	2	
$pn \to K^{*,0} + \pi^+$	2	
$pn \to \pi^+ + \phi$	2	
$pn \to \pi^0 + \rho^+$	2	
$pn \to K^+ + \pi^0$	2	
$pn \to K^{*,+} + \pi^0$	2	
$pn \to \eta + \rho^+$	2	
$pn \to \eta + K^+$	2	
$pn \to \eta + K^{*,+}$	2	
$pn \to \rho^+ + \rho^0$	2	
$pn \to K^+ + \rho^0$	2	
$pn \to K^{*,+} + \rho^0$	2	
$pn \to \rho^+ + \omega$	2	
$pn \to \eta' + \rho^+$	2	
$pn \to K^0 + \rho^+$	2	
$pn \to K^{*,0} + \rho^+$	2	
$pn \to \rho^+ + \phi$	2	
$pn \to K^+ + \omega$	2	
$pn \to K^{*,+} + \omega$	2	
$pn \to \eta' + K^+$	2	
$pn \to \eta' + K^{*,+}$	2	
$pn \to K^+ + K^0$	2	
$pn \to K^+ + K^{*,0}$	2	
$pn \to K^+ + \phi$	2	
$pn \to K^{*,+} + K^0$	2	
$pn \to K^{*,+} + K^{*,0}$	2	

- Past searches assumed only SM particles in external final states… **turns out field a lot richer**

[Heeck, **VT**, *Phys.Rev.D*, (2020)]

New Broad Program at SK/HK with Non-Canonical Nucleon Decays

Test of Light Physics: axions, dark photons, sterile ν's, scalar dark matter …

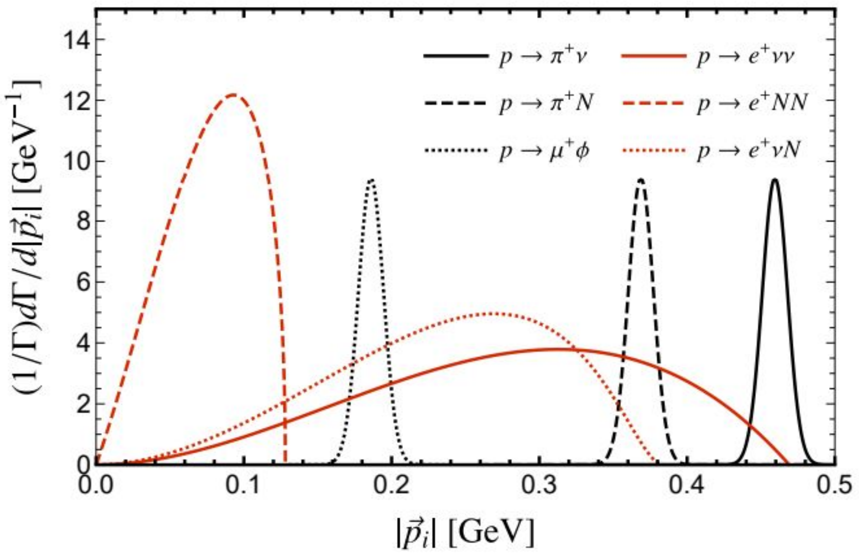
$\mathcal{O}$	Operator	$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$\mathcal{O}_{d^2uN}$	$\epsilon^{abc}(d_a N)(d_b u_c)$	$(1,1)$	6	$p(n) \to \pi^{+(0)} N$	sterile neutrinos
$\mathcal{O}_{Dd^2u\bar{N}}$	$\epsilon^{abc}(d_a \sigma_\mu N^\dagger)(d_b D^\mu u_c)$	$(1,-1)$	7	$n \to N\gamma$ $p(n) \to \pi^{+(0)} N\gamma$	sterile neutrinos
$\mathcal{O}_{du^2e\phi}$	$\epsilon^{abc}(d_a u_b)(e u_c)\phi^\dagger$	$(1,1)$	7	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$\mathcal{O}_{d^2Q\bar{L}X}$	$\epsilon^{abc}(Q^i_a \sigma^\mu d_b)(d_c L^\dagger_i)X_\mu$	$(1,1)$	7	$n \to \nu X$ $p(n) \to \nu\pi^{+(0)} X$ $n \to e^+\pi^- X$	dark photons
$\mathcal{O}_{dQ^2\bar{L}\bar{H}\phi}$	$\epsilon^{abc}(Q^i_a Q^j_b)(L^\dagger{}_i d_c)H^\dagger_j \phi^\dagger$	$(1,1)$	8	$n \to \nu\phi$ $n \to e^+\pi^-\phi$	dark scalars, majorons
$\mathcal{O}_{Dd^2Q\bar{L}a}$	$\epsilon^{abc}(\partial^\mu a)(Q^i_a \sigma^\mu d_b)(d_c L^\dagger_i)$	$(1,1)$	8	$n \to \nu a$ $p(n) \to e^+\pi^{0(-)} a$ $p(n) \to e^+\pi^{0(-)} a$	axion-like particles
$\mathcal{O}_{Dd^2u\bar{N}a}$	$\epsilon^{abc}(\partial^\mu a)(d_a \sigma_\mu N^\dagger)(d_b u_c)$	$(1,-1)$	8	$n \to Na$ $p(n) \to \pi^{+(0)} Na$	axion-like particles with sterile neutrinos
$\mathcal{O}_{duQe\bar{L}\bar{N}}$	$\epsilon^{abc}(e u_a)(Q^i_b \sigma_\mu d_c)(N^\dagger \sigma^\mu L^\dagger_i)$	$(1,1)$	9	$p \to e^+\nu N$ $n \to e^+e^- N$	sterile neutrinos
$\mathcal{O}_{du^2eN^2}$	$\epsilon^{abc}(d_a u_b)(e u_c)(NN)$	$(1,3)$	9	$p \to e^+ NN$	sterile neutrino

** don't require external interactions like "induced" nucleon decays*

- Many novel possibilities mediated by motivated BSM particles
- Multi-nucleon decays possible (di/tri-nucleon…)
- Mixed scenarios possible (e.g. axion + sterile N, ν + dark photon → new minimal invisible mode)
- New tests of light new physics over decades in mass below ~ few GeV

[Fridell, Hati, **VT**, 2312.13740 (2023)]

Look for Unusual Kinematic Signatures



Example: $m_N = 400$ MeV and dark scalar mass $m_\phi = 700$ MeV.

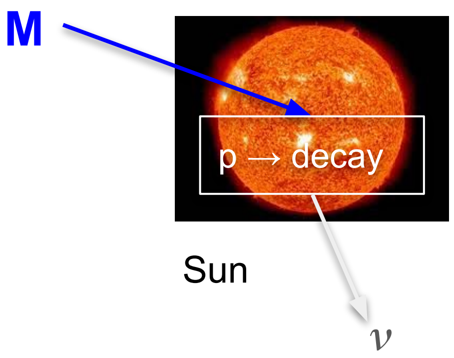
→ conventional searches can misinterpret or even completely miss

[Fridell, Hati, **VT**, 2312.13740 (2023)]

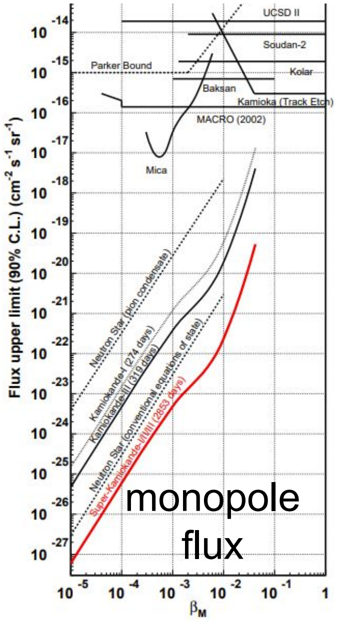
Yet more opportunities: Magnetic Monopoles & Q-Balls

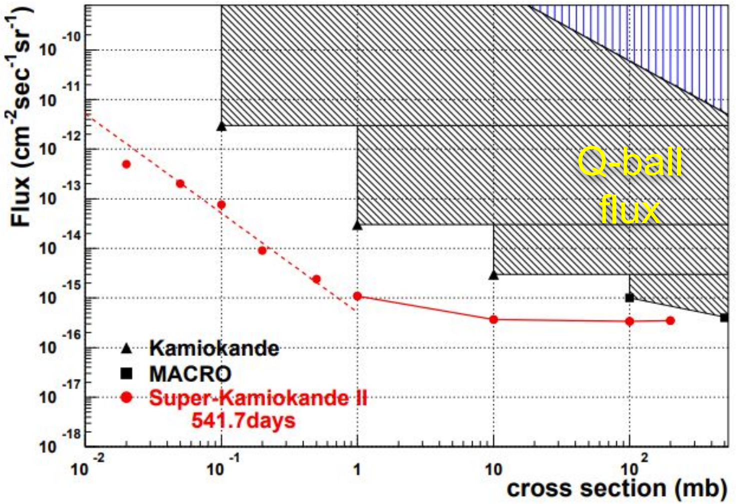
- Heavy monopoles from unified theories can be captured by Sun and induce proton decay via Callan-Rubakov process producing neutrinos
- Q-balls naturally appear from field instabilities in e.g. supersymmetric models, can induce nucleon decay in SK / HK when carry baryon number

$$p \to (\rho^0, \omega, \eta, K^+, \cdots) + e^+(\text{or} \ \ \mu^+)$$



[Ueno+ (Super-K), *Astropart.Phys.*, (2012)]





[Takenaga+ (Super-K), *Phys.Lett.B*, (2007)]

Conclusions

- Super-K and upcoming Hyper-K are spectacular multipurpose experiments, very rich new physics program - discovery machines

- Super-K has already delivered many leading results
  → many unexplored opportunities

→ ***<u>Bright Future for Discoveries !</u>***